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Analysis of the circular phased array of microstrip patches at X-band

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Abstract : An analytical study of a new type of four element circular phased array of circular patch microstrip antenna (CPACPMA) is presented at frequency 10 GHz. The results are obtained both in plasma and in free space medium. Some important antenna parameters like radiation efficiency and directive gain are plotted for different ratios of plasma-to-source frequency. It is observed that radiation properties of CPACPMA are adversely affected for higher values of plasma content. The present study satisfies all the three technical views, *i e.* feasibility, maintainibility and expandability.

Keywords : Circular phased array, microstrip antenna, plasma

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Following the concept of conformal nature of microstrip antennas, we propose the circular phased array of circular patch microstrip antenna (CPACPMA) which possesses potential applications in many systems. The antenna radiation falls gradually from its free space value to a total cutoff with the increase in the ratio of plasma-to-source frequency in plasma [1,2]. In the present paper, the radiation performance of four element CPACPMA is studied in free space as well as in plasma media. The field patterns, radiation efficiency and directive gain are obtained for different ratios of plasma-to-source frequency. It is concluded that radiation properties are altered to a great extent for sufficiently large values of plasma frequency (approximately equal to source frequency).

The configuration and the coordinate system of the CPACPMA are shown in Figure 1. It consists of four identical elements on a dielectric substrate of thickness h and substrate permittivity $\varepsilon_r = 3.55$, placed in X–Y plane along a circular ring of radius ρ. The radius of each array element is a. The array elements are taken for the point M which moves such that it occupies uniform angular distance ($\phi_m = \pi/2$) between all the four elements from X-axis. Each patch can be excited by a microstrip transmission line connected to the edge or by a coaxial line from the back at the plane $\phi = 0$. Among the

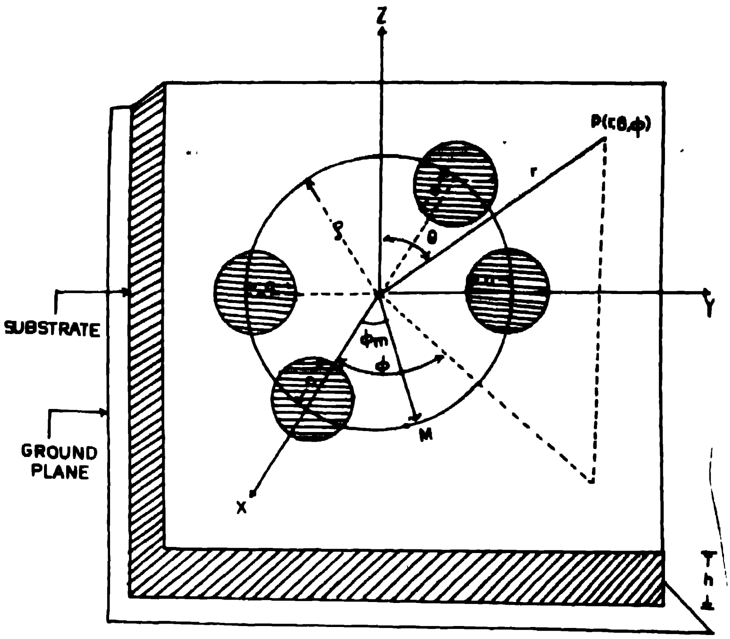

Figure 1. Configuration and coordinate system of four element CPACPMA.

various modes that may be excited in such a disc resonator, it is to consider TM_{nm} mode with respect to Z-axis. Here n and m are the mode numbers associated with preferred directions respectively [2].

Following Bhatnagar and Gupta [1] and Balanis [3], using linearized hydrodynamic theory of plasma [4] and neglecting coupling between the elements [5], the far-zone field expressions for the CPACPMA are obtained as follows

EM mode :

$$E_{\theta t} = j^n V_0 a \beta_e \gamma_0 \frac{\exp(-j\beta_e r)}{2r} \cos n\phi \, J_n'(\beta_e a \sin\theta)$$

$$\times \sum_{m=1}^{4} \exp j \left\{\beta_e \rho \sin\theta \cos(\phi - \phi_m) + \beta_1\right\} \tag{1}$$

$$E_{\phi t} = j^n V_0 a \beta_e \gamma_0 \frac{\exp(-j\beta_e r)}{2r} \sin n\phi \cos\theta \frac{J_n(\beta_e a \sin\theta)}{(\beta_e a \sin\theta)}$$

$$\times \sum_{m=1}^{4} \exp j \left\{\beta_e \rho \sin\theta \cos(\phi - \phi_m) + \beta_1\right\}; \tag{2}$$

$$\text{P-mode:}\quad E_{p\ell} = (-j)^{n+2}\, \frac{60\pi(1-A^2)}{A} \left(\frac{c}{v}\right) \gamma_0 K_1^2 n J_n(K_1 a)\, \frac{\exp(-j\beta_p r)}{r}$$

$$\times \frac{\sin(\beta_p h \cos\theta)}{\beta_p h \cos\theta} J_n(\beta_p a \sin\theta) \sin n\phi$$

$$\times \sum_{m=1}^{4} \exp j\left\{\beta_p \rho \sin\theta \cos(\phi - \phi_m) + \beta_1\right\} \tag{3}$$

where γ_0 is uniform amplitude excitation coefficient of the elements and other symbols stand for same quantities as given earlier [2].

Field patterns :

The total field pattern $R(\theta, \phi)$ is generally obtained from the relation

$$R(\theta, \phi) = \left|E_{\theta t}\right|^2 + \left|E_{\phi t}\right|^2. \tag{4}$$

The values of $|E_{\theta t}|^2$ and $|E_{\phi t}|^2$ are calculated using input data f_r = 10 GHz, a = 0.47 cm, ρ = 4.78 cm, ε_r = 3.55, n = 1 and $\beta_1 = \pi/2$. The values of ϕ_m are chosen such that it has uniform and finite phase difference between two consecutive elements *i.e.* ϕ_1, ϕ_2, ϕ_3

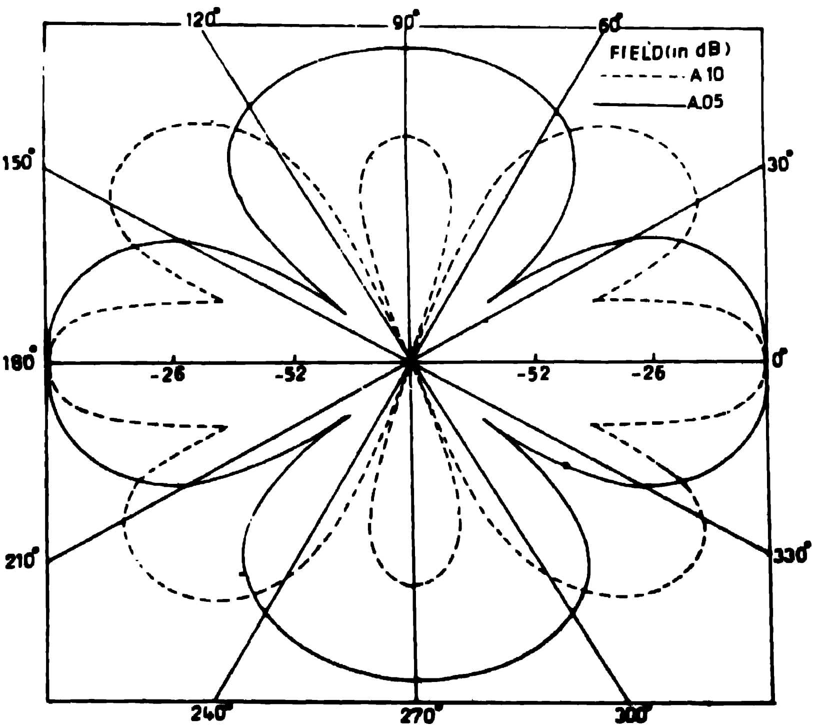

Figure 2. Variation of $|E_{\theta t}|^2$ for A = 1.0 (free space) and A = 0.5 (plasma) for four element CPACPMA.

and ϕ_4 have values $\pi/2$, π, $3\pi/2$ and 2π respectively from X-axis. The results obtained from eq. (4) are computed and plotted in Figures 2 and 3 respectively, for two different planes (*i.e.* $\phi = \pi/2$ and $\phi = 0$) for $A = 1.0$, *i.e.* in free space and $A = 0.5$ *i.e.* in plasma. The plasma

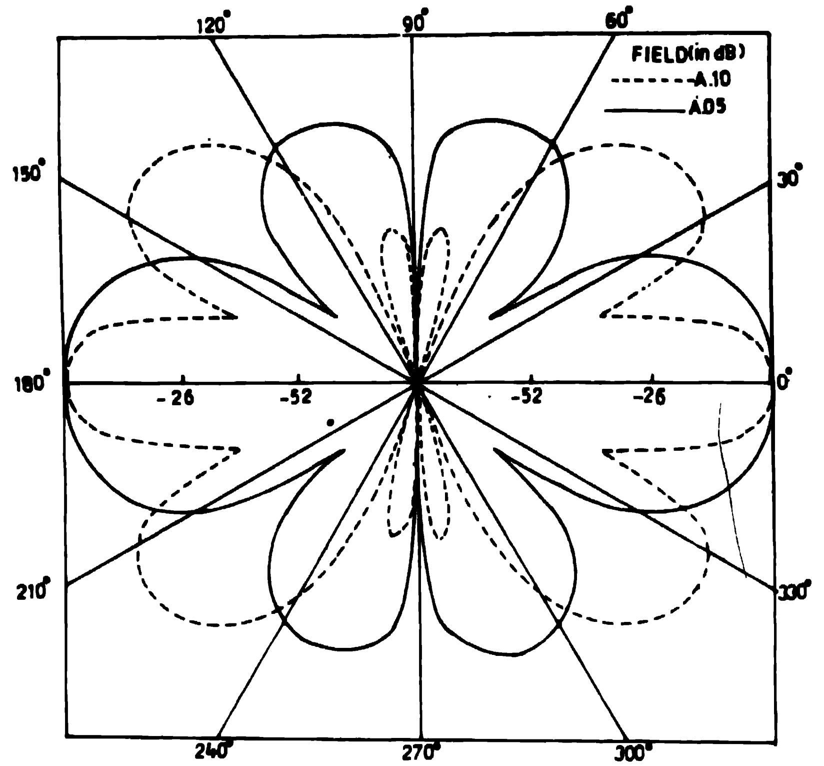

Figure 3. Variation of $| E_{\phi t} |^2$ for $A = 1.0$ (free space) and $A = 0.5$ (plasma) for four element CPACPMA.

mode fields are computed for $A = 0.5$ in $\phi = \pi/2$ plane at $\theta = 0.5°$ increments in a small interval of 10°. Assuming that there is no lobe narrower than 0.5°, the normalized values of the p-mode field patterns are plotted between $\theta = 50°$ to $60°$ in Figure 4.

Radiation efficiency :

The expressions for radiation conductance of electromagnetic mode G_e and plasma mode G_p may be expressed in the same way as in Ref [2], taking I_1 and I_2 as

$$I_1 = \int_{\theta}^{2\pi} \int_{0}^{\pi} \left[\left\{ J_n'(\beta_e a \sin\theta) \cos n\phi \right\}^2 + \left\{ \frac{J_n(\beta_e a \sin\theta)}{\beta_e a \sin\theta} \sin n\phi \cos\theta \right\}^2 \right]$$

$$\times \left[\sum_{m=1}^{4} \exp j \left\{ \beta_e \rho \sin\theta \cos(\phi - \phi_m) + \beta_1 \right\} \right]^2 \sin\theta \, d\theta d\phi \qquad (5)$$

and
$$I_2 = \int_0^{2\pi}\int_0^{\pi}\left[\frac{\sin(\beta_p h\cos\theta)}{\beta_p h\cos\theta} J_n(\beta_p a\sin\theta)\sin n\phi\right]^2$$

$$\times\left[\sum^{4} \exp j\left\{\beta_p\rho\sin\theta\cos(\phi-\phi_m)+\beta_1\right\}\right]^2 \sin\theta\, d\theta d\phi. \tag{6}$$

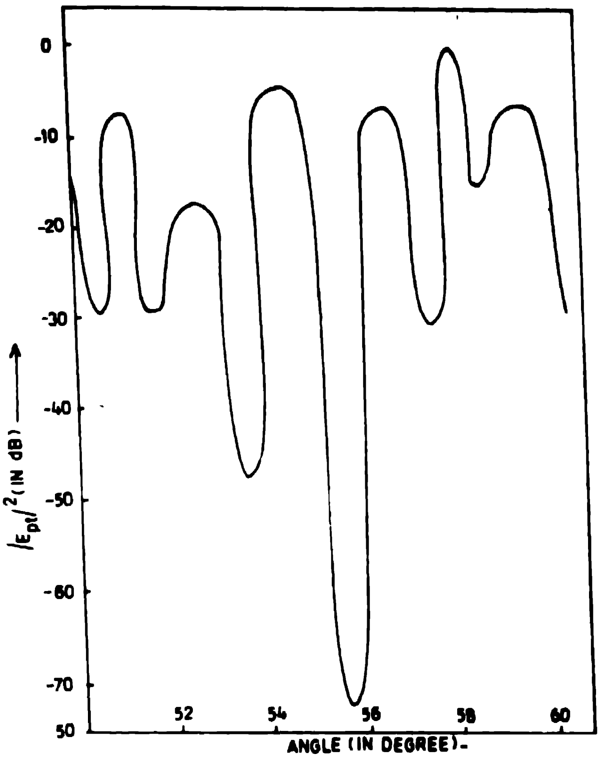

Figure 4. Plasma mode field pattern $|E_{pt}|^2$ for $A = 0.5$ for four element CPACPMA.

Now, the radiation efficiency of the array antenna η (%) in plasma medium can be calculated with the help of the expression given as

$$\eta = \frac{\text{Useful power in plasma}}{\text{Total power}} = \frac{G_e}{G_e + G_p} \times 100\,\%. \tag{7}$$

Directive gain :

The directive gain of the CPACPMA is expressed as

$$D_e = \frac{4\pi M_e}{\int_0^{2\pi}\int_0^{\pi} M_e \sin\theta\, d\theta d\phi} \quad \text{for } \theta = \frac{\pi}{4},\ \phi = 0 \tag{8}$$

with
$$M_e = \left[\left\{J_n'(\beta_e a\sin\theta)\cos n\phi\right\}^2 + \left\{\frac{J_n(\beta_e a\sin\theta)}{\beta_e a\sin\theta}\sin n\phi\cos\theta\right\}^2\right]$$
$$\times\left[\sum_{m=1}^{4}\exp j\left\{\beta_e\rho\sin\theta\cos(\phi-\phi_m)+\beta_l\right\}\right]^2 \qquad (9)$$

The calculated values of radiation efficiency (η) and directive gain (D_e) are plotted in Figure 5 for different values of plasma-to-source frequency (ω_p/ω_o).

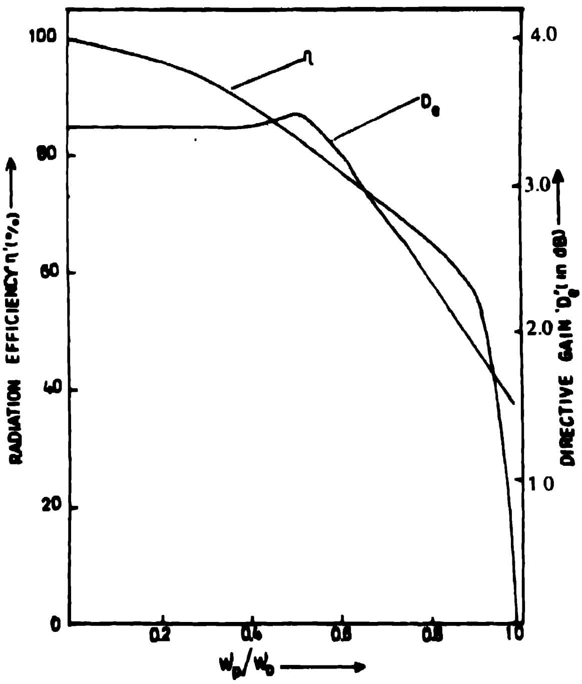

Figure 5. Variation of radiation efficiency η and directive gain D_e with plasma-to-source-frequency for four element CPACPMA.

From Figures 2 and 3, it is obvious that the presence of plasma medium modifies the radiation characteristics of CPACPMA significantly. Considerable redistribution of field intensities has been found in figures. It is also noticed that there is symmetric change in all the four quadrants resulting the unchanged maxima at $\theta = (0°–180°)$ direction. In case of $|E_\phi|$, the normalized relative power is divided into two equal small lobes between $\theta = 50°$ to $\theta = 130°$ which causes a minima at $\theta = 90°$. The p-mode field patterns represent a large number of lobes in a small interval of 10° (from 50° to 60°). Figure 5 shows a considerable plasma effect on the radiation conductance which in consequence results a fall in the radiation efficiency of antenna. In other words power radiated in p-mode is appreciably larger than EM mode for higher values of plasma frequency. The directive gain of CPACPMA is higher than that of single element patch antenna but it also decreases sharply when the plasma frequency occupies almost half of the value of source frequency. The present study is supposed to be very useful especially for space vehicles because such type of arrays can be mounted on-board the curved surface too, *i.e.* no flat surface of a vehicle is needed.

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